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High Resolution X-Ray Spectroscopy of Seyfert 2 Galaxies

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Abstract. X-ray spectroscopy of Seyfert 2 galaxies provides an excellent probe of the circumnuclear environment in active galactic nuclei. The grating experiments on both Chandra and XMM-Newton have now provided the first high resolution spectra of several of the brightest Seyfert 2's. We present Chandra HETG data on Markarian 3, and XMM-Newton RGS data on NGC 1068. In both cases, the spectra are dominated by emission lines due to radiative recombination following photoionization, photoexcitation, and fluorescence. There is no evidence for any significant contribution from collisionally-heated gas.

1. Introduction

In standard models of active galactic nuclei, Seyfert 2 galaxies are interpreted as systems viewed at sufficiently high inclination angles that the central continuum source is obscured by the surrounding dusty torus (e. g., Krolik 1999). However, residual soft X-ray emission is observed from many of these systems. This must originate in the unobscured nuclear vicinity, or perhaps in other regions of the galaxy. While one expects some soft X-ray emission to be produced by reprocessing of the strong continuum flux in the circumnuclear environment, collisionally-heated gas associated with starburst regions might also provide an important contribution (e. g., Wilson et al. 1992).

High resolution X-ray spectroscopy provides the least ambiguous means of distinguishing between these two interpretations. Discrete spectral features formed in collisional plasmas are qualitatively different from those formed in photoionized gas (Liedahl 1999). In collisional plasmas, emission lines are primarily produced by electron impact excitation from the ground state, which favors strong resonance transitions. Fe L-shell transitions are especially prominent. In photoionized plasmas, the electron temperature and density are too low for excitation by electron impact, and the lines are produced mostly via

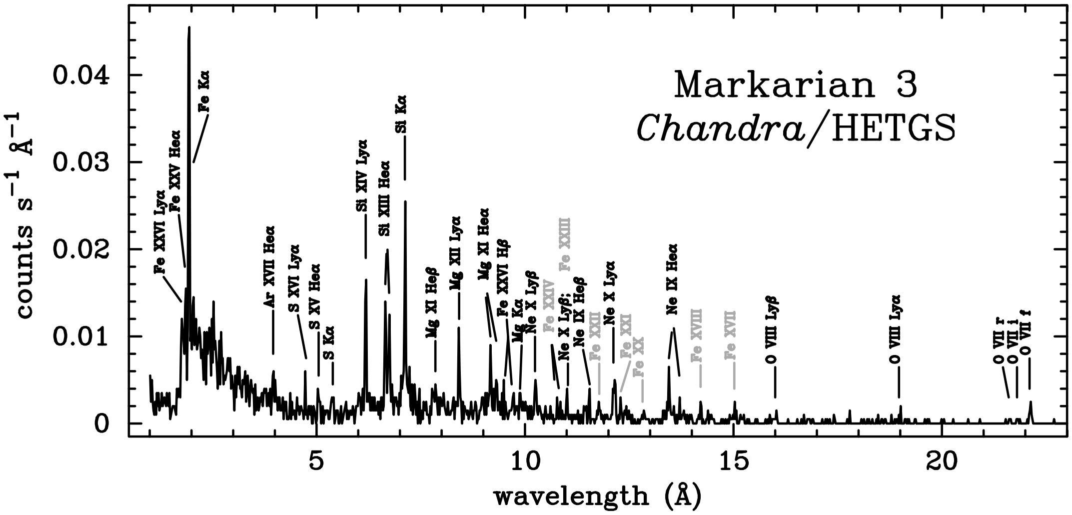

Figure 1. Chandra HETG spectrum of Markarian 3.

radiative cascades following recombination, which favors the lowest-lying multiplet levels, thereby producing forbidden transitions. Also, Fe L lines are much weaker than hydrogenic and heliumlike K-shell transitions of lower Z elements. Another characteristic difference involves the radiative recombination continua (RRC). In collisional plasmas, these are broad weak features, barely discernible above the bremsstrahlung continuum. In photoionized plasmas, the RRC are much narrower and far more prominent (Liedahl and Paerels 1996).

The grating experiments on Chandra and XMM-Newton have provided the first X-ray spectra of Seyfert 2's with sufficient resolution and sensitivity to investigate these issues in detail. Here we present Chandra HETG spectra of Markarian 3 and XMM-Newton RGS spectra of NGC 1068. The data are consistent with all emission arising in photoionized gas. We can use these spectra to derive sensitive constraints on the structure of the circumsource environment.

2. Markarian 3

The Chandra HETG spectrum of Markarian 3 is shown in Figure 1 (Sako et al. 2000). A variety of narrow features are readily discernible and are explicitly labeled in the figure. These include Ly series transitions of hydrogenic O, Ne, Mg, Si, S, and Fe, heliumlike complexes of O, Ne, Mg, Si, S, Ar, and Fe, near-neutral fluorescence Kα lines of Mg, Si, S, and Fe, and a few weak Fe L lines for a range of charge states (Fe XVII through XXIV).

The Heα complexes are especially interesting. For O VII, the forbidden line is clearly the strongest, and the relative line ratios agree with the values expected for pure recombination (Porquet & Dubau 2000). For both Ne IX and Si XIII, the resonance lines are roughly comparable to the forbidden lines, but the ratios are still not as high as expected for electron impact excitation. This suggests possible contributions from both recombination and collisional excitation emission from the same plasma or spatially-distinct plasmas. The presence of the Fe L features might also bolster that interpretation.

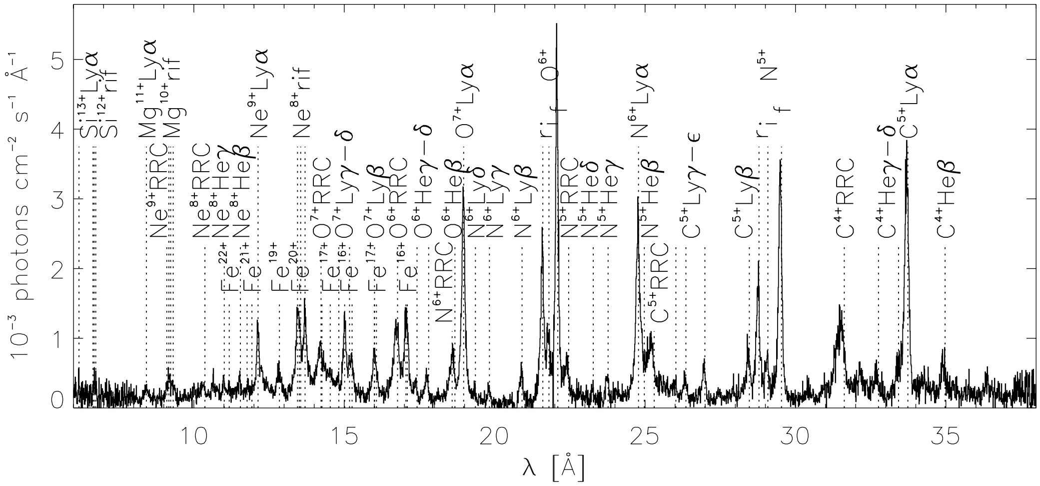

Figure 2. XMM-Newton RGS Spectrum of NGC 1068.

However, we are firmly convinced that this is *not* what is happening in this spectrum. Both the heliumlike resonance lines and the Fe L lines are not produced collisionally, but instead are photoexcited by the central continuum radiation. Two major clues lead us to this interpretation: (1) The Fe L lines are too weak relative to the heliumlike resonance lines to be consistent with electron impact excitation, unless we significantly reduce the iron abundance in the putative collisional component. (2) The specific Fe L lines observe are all 3d–2p and 3p–2s. These have high oscillator strengths, and are the most prominent features expected for photoexcitation. There are no accompanying 3s– 2p transitions, which have much lower oscillator strengths. In collisional plasmas, the two sets of transitions have near comparable line intensities.

At low to intermediate line optical depths, photoexcitation and recombination provide comparable contributions to the X-ray line spectrum of photoionized gas. This interpretation suffices for Markarian 3. We see no conclusive evidence for a contribution from collisional gas.

3. NGC 1068

The XMM-Newton RGS spectrum of NGC 1068 is shown in Figure 2 (Kinkhabwala et al. 2001a). We see a very line-rich spectrum dominated by hydrogenic and heliumlike lines (C through Si), accompanied by weak Fe L-shell transitions. In addition, we see very prominent RRC. All RRC for the hydrogenic and heliumlike charge states of C, N, O, and Ne are detected.

The narrow RRC provide unambiguous evidence that most of the X-ray emission we are observing is produced in photoionized gas. This conclusion is supported by the Heα complexes, in which the forbidden line is brighter than the resonance. The ratios of the forbidden line intensities to the RRC intensities agree with expectations for recombination cascades.

Nevertheless, as for Markarian 3, recombination alone does not provide a good quantitative fit to the entire NGC 1068 spectrum. The heliumlike resonance lines are still too bright relative to the forbidden lines, and the Fe L lines are brighter than would be expected for purely recombining gas. Here again, we can explain all of these features by allowing for additional contributions from photoexcitation. Conclusive evidence for this comes from the hydrogenic line series: The higher series lines are observed to be significantly brighter relative to Lyα than is expected for either recombining gas or collisionally-excited gas. This is a natural consequence of photoexcitation at intermediate optical depths due to saturation of the highest oscillator strength lines.

We have developed a fully self-consistent model for the NGC 1068 spectrum in terms of a photoionized medium which correctly accounts for both the photoexcitation and radiative recombination contributions (Kinkhabwala et al. 2001a, Behar et al. 2001). Individual column densities and velocity distributions for each ion are left as free parameters. The model provides an amazingly good fit to these high statistics data. Fits to the earlier Chandra HETG spectra of Markarian 3, NGC 4151 (Ogle et al. 2000), and the Circinus galaxy (Sambruna et al. 2000) as well as to a recent observation of NGC 4507 yield similar results (Kinkhabwala et al. 2001b). In particular, we find that the Ogle et al. (2000) conclusion that the NGC 4151 spectrum indicates the presence of hot collisional gas is incorrect. All of the features in the spectra of all Seyfert 2 galaxies so far observed with Chandra and XMM are consistent with fluorescence of cold gas and photoexcitation and recombination cascades in photoionized gas.

4. Conclusion

The high resolution X-ray spectra of Seyfert 2 galaxies display a wealth of emission features produced by fluorescence, photoexcitation, and recombination cascades in radiatively-driven gas. There is no evidence for measureable contributions from hot collisionally-ionized gas in any of the sources which have been studied to date. Further observations of this kind should be very helpful in elucidating the nature of the circumsource medium in active galactic nuclei.

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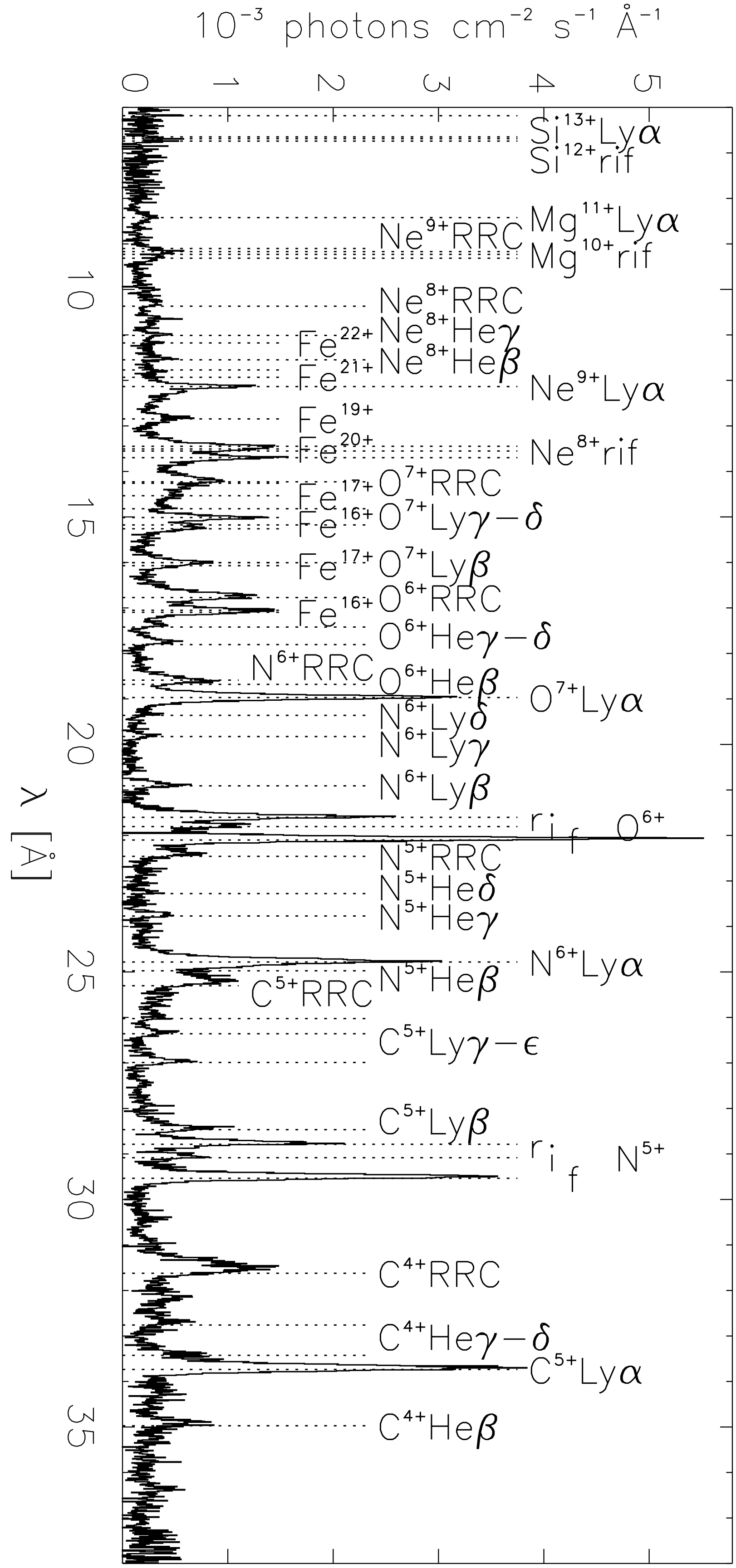

10^-3 photons cm^-2 s^-1 Å^-1
0
1
2
3
4
5
λ [Å]
10
15
20
25
30
35
Si^13+ Lyα
Si^12+ rif
Mg^11+ Lyα
Ne^9+ RRC
Mg^10+ rif
Ne^8+ RRC
Fe^22+
Ne^8+ Heγ
Fe^21+
Ne^8+ Heβ
Ne^9+ Lyα
Fe^19+
Fe^20+
Ne^8+ rif
O^7+ RRC
Fe^17+
Fe^16+
O^7+ Lyγ−δ
Fe^17+
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